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STARSAT: A Project to Evaluate Ground Tracking of Small Objects in Space (MSFC Center Director's Discretionary Fund Final Report, Project No. 00–11)

J.W. Campbell, M.R. Carruth, and T.M. Freestone
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May 2004

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LIST OF ACRONYMS AND SYMBOLS

AEOS	advanced electro-optics system
Ag/FEP	silvered Teflon
CNR	carrier-to-noise ratio
CO_2	carbon dioxide
GPS	global positioning system
HI-CLASS	high-performance CO_2 ladar surveillance sensor
LEO	low-Earth orbit
LWIR	long wavelength infrared
MSFC	Marshall Space Flight Center
MSSS	Maui space surveillance site
OPM	output pulse monitor
TM	Technical Memorandum
T/R	transmit/receive

TECHNICAL MEMORANDUM

STARSAT: A PROJECT TO EVALUATE GROUND TRACKING OF SMALL OBJECTS IN SPACE (MSFC Center Director's Discretionary Fund Final Report, Project No. 00–11)

1. INTRODUCTION

The Directed Energy Directorate of the Air Force Research Laboratory and NASA Marshall Space Flight Center (MSFC) are considering a series of joint flight experiments to demonstrate acquisition and tracking of small Earth-orbiting objects specifically assessing orbital position accuracy. The plan will be to place a small microsatellite in orbit and acquire and track it with ground systems. The satellite will be equipped with an onboard global positioning system (GPS) satellite receiver that will provide independent position data for comparison with that obtained from the ground tracking systems. The primary ground system will utilize the 12-J, 15-Hz high-performance CO_2 ladar surveillance sensor (HI-CLASS) system on the 3.67-m aperture advanced electro-optics system (AEOS). This system is part of the Maui space surveillance site (MSSS) system on the summit of Haleakala, Maui, HI. The objectives of these experiments are to provide accurate range and signature measurements of calibration spheres, demonstrate high-resolution tracking capability of small objects, and provide precision low-Earth orbit (LEO) drag data. Ancillary benefits include calibrating radar and optical sensors, completing satellite conjunction analyses, supporting orbital perturbation analyses, and comparing radar and optical signatures (cross sections). This Technical Memorandum (TM) describes the GPS technology development, the experiment operating concept, the current status of the experiment, and an overview of the HI-CLASS AEOS capabilities.

2. HI-CLASS ADVANCED ELECTRO-OPTICS SYSTEM

The AEOS facility, a description of its capabilities to support multiple users, and the location of the HI-CLASS system within the AEOS are shown in figure 1. The HI-CLASS AEOS system is situated in suite 4 and has available a large optical table suitable for other visiting experiments. This table has access to the AEOS and HI-CLASS beam trains via a remote-controlled mirror assembly.

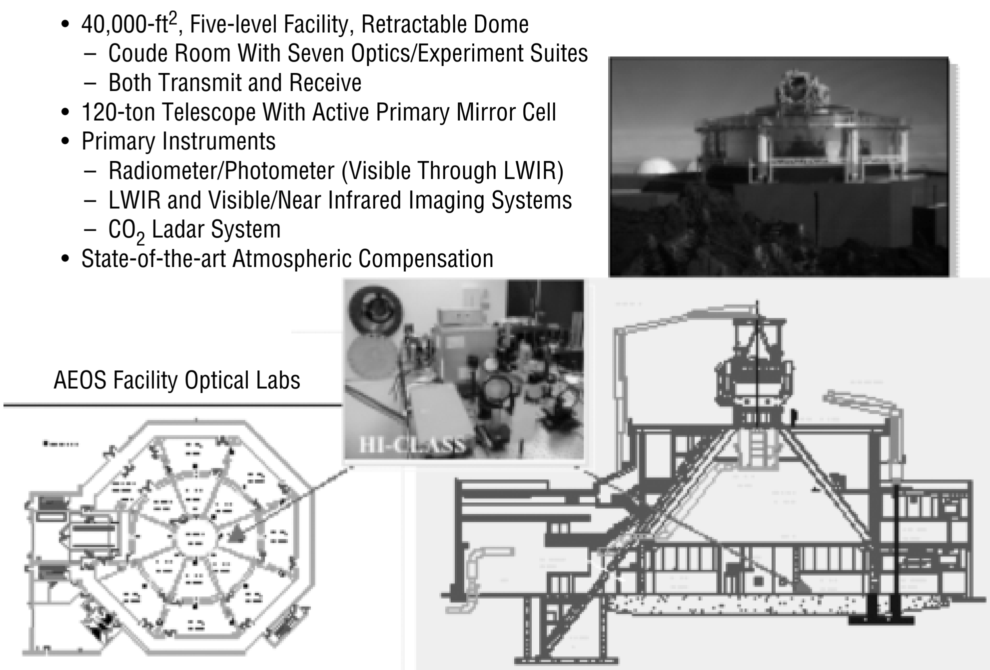

Figure 1. AEOS facility with HI-CLASS system.

The parameters of the HI-CLASS AEOS are shown in table 1. The moderate power HI-CLASS AEOS generates multiple, coherent waveforms for precision satellite tracking and characterization of space objects smaller than 30 cm at ranges to 1,000 km. The carrier-to-noise ratio (CNR) at fixed range and transmitter energy scales with diameter. Significant increases in the CNR, range, and gain over other ladar systems at the MSSS are anticipated.

Table 1. HI-CLASS AEOS parameters.

Power oscillator, single-channel receiver/processor, controller (no amplifier)	Precision 1-m^2 satellite tracking	To 10,000 km
12-J, 15-Hz wideband system Pulse-tone and pulse-burst waveforms	Measurement accuracy	Range (m) ±4 Range rate (m/s) ±1
11.13-µm wavelength Single 4-µs pulse width	Range-Doppler imaging spatial resolution	Submeter
Single resonator Heterodyne receiver imaging capability (≈0.5-GHz bandwidth)	Range-Doppler imaging range	To 5,000 km
"Holey" mirror T/R switch	Small object tracking to 1,000 km	1 cm^2

The HI-CLASS AEOS has a power oscillator producing ≈180 W as the transmitter. The transmitter can switch from pulse-tone to pulse-burst waveforms at its system repetition rate of 15 Hz. In addition, the transmitter is equipped with an output pulse monitor (OPM) that uses coherent detection to capture the output waveform phase and amplitude to assist in signal processing. Transmitter coupling to the beam director incorporates a transmit/receive (T/R) switch to effect isolation between the high output power and the extremely sensitive, heterodyne receiver. The HI-CLASS AEOS employs a mirror with a small, central aperture as the T/R switch by taking advantage of the point-ahead angular offset between the transmitted and return beams.

The heterodyne receiver employs a wideband, quad-element, Hg:Cd:Te detector illuminated with a local oscillator to functionally achieve a photon counting capability as well as to extract the Doppler shift of the target. The microwave receiver amplifies band limits and Doppler tracks the return signal; i.e., it utilizes a variable frequency microwave oscillator to shift the return signal to baseband. The nominal bandwidth is 40 MHz for the pulse-tone waveform and 750 MHz for the pulse-burst waveform. The microwave receiver generates in-phase and quadrature outputs to facilitate processing.

The processor digitizes and records the narrow and wideband waveforms at the full system repetition rates. In addition, it captures the OPM signals along with all system operating and status parameters (more than 100) at the respective system repetition rates. The HI-CLASS AEOS will generate real-time range and range-rate estimates at 15 Hz.

The HI-CLASS AEOS will provide precision metrics and range-amplitude measurements of LEO objects. The HI-CLASS AEOS operates purely as a tracking and imaging ladar at a fixed wavelength of 11.13 µm. Since orbiting objects are not generally amenable to inverse, synthetic aperture-type imaging, the waveforms were simplified to provide a tracking and range-amplitude imaging capability only. These capabilities are derived from a 5-µs injection-seeded (acquisition), pulse-tone waveform and a mode-locked, pulse-burst imaging waveform with the same 5-µs envelope duration. The transmitter will provide average powers of ≈180 W (12 J at 15 Hz) in an oscillator configuration.

3. CONCEPT FOR EXPERIMENT

This investigation should answer important questions about tracking small, hypervelocity objects in LEO through a turbulent, nonlinear atmosphere. In the first experiment, a GPS and laser beacon-instrumented microsatellite (fig. 2) ≈25 cm in diameter will be deployed from a Space Shuttle Hitchhiker canister or other suitable launch means.

Orbiting in LEO, the microsatellite will pass over the AEOS several times per 24-hr period. An onboard orbit propagator will activate the GPS unit and a visible laser beacon at the appropriate times. The HI-CLASS AEOS will detect the microsatellite as it rises above the horizon using acquisition vectors generated by the space track network from prior orbit passes. The visible laser beacon on the satellite will be used by the AEOS to fine tune the tracking parameters. Continuous track and ladar data measurements will occur throughout the pass. This operational approach should maximize visibility to the ground-based laser while allowing battery life to be conserved, thus extending the lifetime of the satellite. GPS data shall be transmitted to the ground, providing independent location information for the microsatellite down to submeter accuracies.

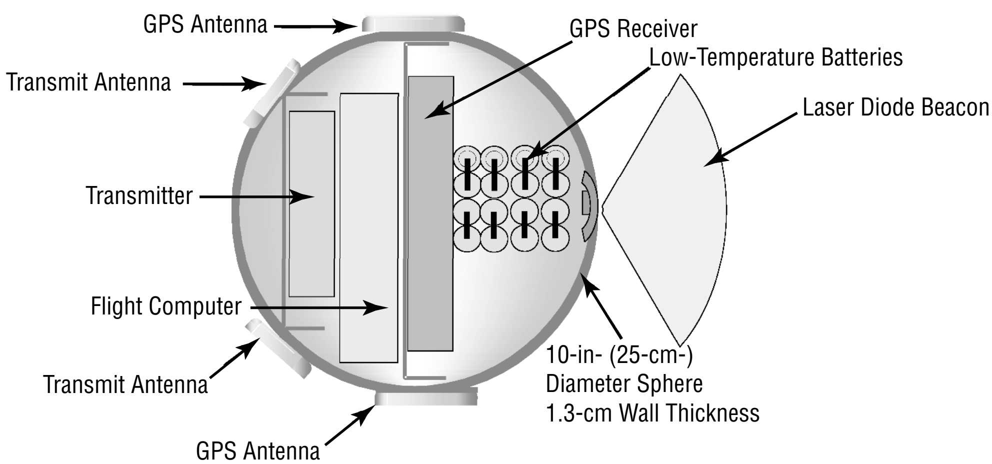

Figure 2. Calibration sphere concept.

4. ORBIT ANALYSIS

A key determination made from orbital analysis is that the microsatellite will only be visible to the MSSS system one to six times per day, depending on altitude, and only for a few minutes each time, as shown in figure 3. This analysis was based on a typical Shuttle orbit with a 51.6° inclination. If relying only on visual observation, the HI-CLASS can only track during morning or evening terminator periods, but there are ongoing activities to determine if the use of an infrared acquisition sensor could extend the observing period. Utilization of the onboard laser diodes will also allow acquisition at other times. A primary objective of the microsatellite design is to extend its orbital lifetime as much as possible to ensure ample periods of observation.

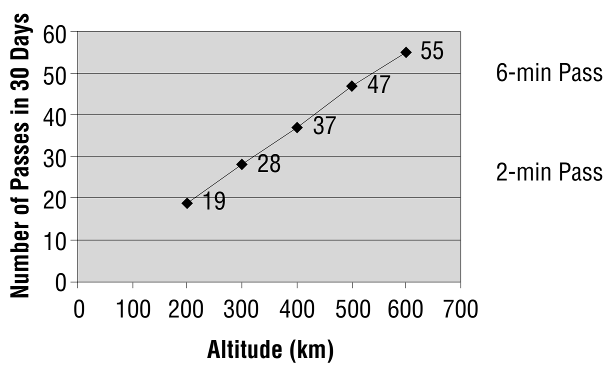

Figure 3. Number (duration) microsatellite passes versus orbit altitude.

5. GLOBAL POSITIONING SATELLITE CONSIDERATION

A space-capable GPS receiver will be placed aboard the microsatellite to provide data for both real-time and postprocessed position and velocity information. A GPS receiver design will be selected that will fit into the 25-cm-diameter sphere. To save power as the microsatellite orbits the Earth, it is cycled on and off at a predetermined rate by the flight computer and orbit propagator. It will also be functioning during passes over Maui for direct comparison with ground-based data. The GPS position and raw data are stored in memory. When the GPS receiver and flight computer determine that the microsatellite is over a ground station, the flight computer commands the radio frequency transmitter to turn on, and the contents of the memory are transmitted to the ground. Earth-based GPS postprocessing software will then be used to provide the required navigation output data, including submeter positional accuracy. This technique has been successfully addressed by the manufacturers and tested in MSFC laboratories, but simulations to address the positional accuracy are ongoing.

Once on the ground, the GPS data will be sent to a central data collection facility where it will undergo processing to determine the microsatellite position and velocity profile. These data will be sent through a precision orbit determination algorithm and combined with GPS data collected from around the globe by the International Geological Survey's GPS data collection network to provide after-the-fact submeter-level ephemeris information for the microsatellite. This precision orbit determination information will be later used for comparison and evaluation purposes to help calibrate the HI-CLASS AEOS.

Because submeter postprocessed accuracy levels are required of the microsatellite's GPS data, a dual-frequency GPS receiver will be used aboard the microsatellite. This will enable the onboard GPS receiver to measure, rather than mathematically calculate, the ionospheric delay that the GPS signals encounter during their travel from the GPSs to the microsatellite. This is an important consideration; since selective availability has been deactivated, ionospheric delay is now the largest source of GPS measurement uncertainty, thus becoming the largest cause of measurement error for nonmilitary GPS receivers today. Without correcting for this ionospheric delay, postprocessed accuracies at the submeter level would be extremely difficult, if not impossible.

6. LASER BEACON CONSIDERATION

The purpose of a laser beacon is to improve the acquisition process of the microsatellite by the AEOS. A 100-mW laser diode with power regulation circuitry is being considered. Its timer circuitry will turn on as the microsatellite passes over the MSSS. A 50-percent duty cycle is anticipated during turnon. Off-the-shelf alkaline batteries will work if a heat source is provided and the electronics are insulated from the sphere skin. The operating temperature range of the diodes needs to be incorporated into the microsatellite design.

7. POWER CONSIDERATION

Battery life management becomes a principal consideration in the design of the microsatellite. Clearly, a way to turn on and turn off satellite principal functions at the appropriate time is the best means for conserving battery life. Using a GPS, as discussed in section 5, is one convenient approach for determining the appropriate time to turn on and turn off the principal functions. The microsatellite is to be illuminated by the HI-CLASS ladar; therefore, requirements exist for the surface reflectivity of the satellite. This, combined with the desire to minimize cost and complexity, has resulted in no plans for photovoltaics to provide power. Therefore, batteries internal to the satellite will provide power and the active capabilities of the satellite will be dependant on battery life.

The primary power consumers are the GPS receiver and the radio frequency transmitter that will telemeter data to the ground. Both of these are cycled by the onboard flight computer to conserve power and only operate when needed. The GPS receiver is assumed to have a 33-percent duty cycle and a 3.5-W power draw, while the transmitter is assumed to operate once per orbit for 5 min at 20 W. The average continuous power is ≈2.5 W. The size of identified electronics inside the satellite will define the volume remaining for incorporation of batteries. The larger the satellite diameter, the more batteries that can be carried, and the longer the life. However, there is a desire to keep the satellite size small to maintain submeter positional accuracy. Figure 4 shows the projected lifetime of the satellite versus size, assuming a battery energy density of 850 Whr/L and a packing factor of 0.6. Currently, the design for the satellite is 25 cm, meaning the battery will last ≈1.5 mo.

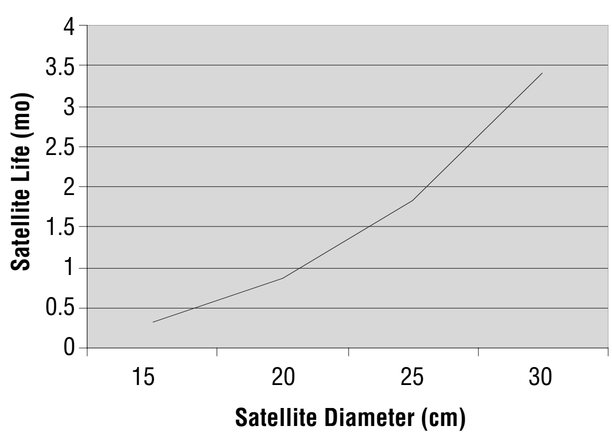

Figure 4. Satellite battery life versus satellite size.

8. THERMAL CONSIDERATION

For the preliminary assessment of thermal conditions for the spherical satellite, a diameter of ≈25 cm was chosen with a wall thickness of 1.3 cm. Conditions were examined for no power expenditure and for a power input in the satellite of 10 W for a third of each orbit. A LEO satellite at a 28° inclination was assumed with spin and an arbitrary spin axis. Various candidate satellite surface coatings were considered that provided a range of emittance and solar absorptance conditions. The silvered DuPont® Teflon® (Ag/FEP) provided such low absorptance and high emittance that the temperatures ran very cold, indicating heaters would be required. Anodized and alodined aluminum surfaces provided better ranges, but in some cases, ranged on the hot side. The chromic anodized aluminum surface provided a temperature range during an orbit of between –13 and 36 °C, making this the most feasible option based on thermal considerations. Section 9 shows that this surface coating also appears to meet surface reflectance requirements for visibility and laser reflectance.

9. PRELIMINARY SPHERE REFLECTANCE RESULTS

There are several factors that drive the sphere reflectance requirements. As mentioned in section 8, there is a desire to have emittance and solar absorptivity values that will allow the satellite's temperature to be controlled passively. This saves heater power and the complexity of having to add heaters. If this can be accomplished without the use of multilayer insulation (MLI), then this also saves volume and complexity. There is a desire to visually acquire the satellite from reflected sunlight if the geometrical conditions allow it. Therefore, good reflectance in the visible wavelength region is important. Also, the reflectance of the satellite at 11.13 μ, the HI-CLASS ladar wavelength, must be sufficient to provide the necessary intensity in the reflected signal for it to be easily measured on the ground. Several candidate thermal control coatings were examined, including Z–93 white paint, Ag/FEP, and different anodized aluminum processes. A chromic anodized aluminum has been preliminarily selected as the outer surface; the thermal aspects of this coating are discussed above. Figures 5 and 6 give the coatings' reflectance as a function of wavelength. This illustrates that the reflectance is both high in the visible and infrared wavelengths of interest.

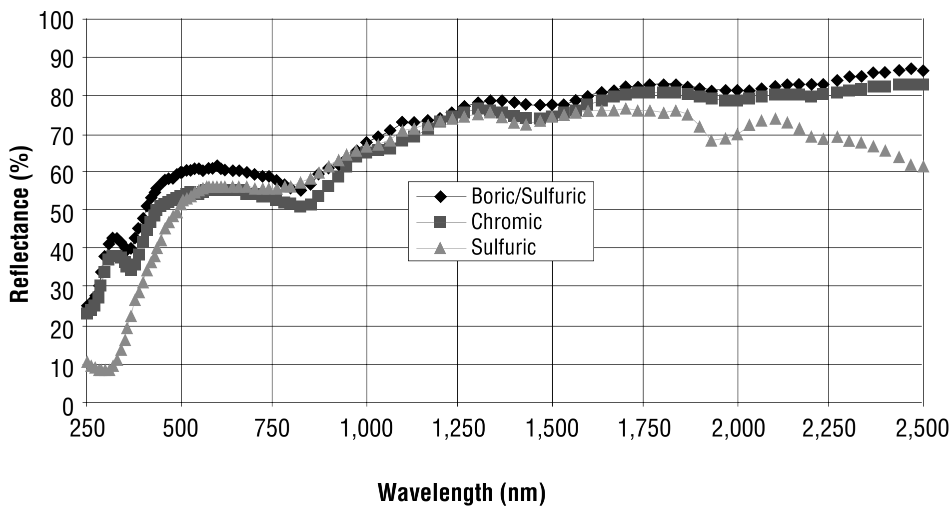

Figure 5. Reflectance of candidate satellite surfaces in the visible.

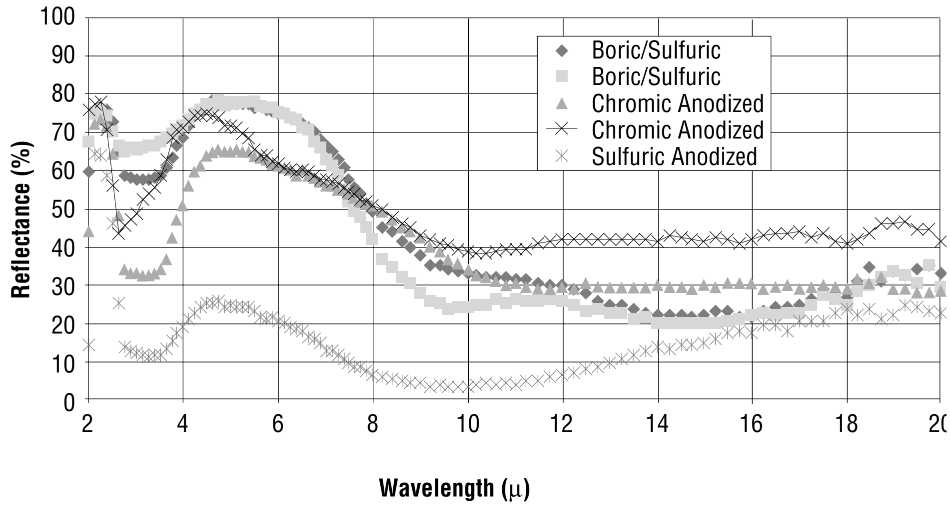

Figure 6. Reflectance of candidate satellite surfaces in the infrared.

10. SUMMARY AND CONCLUSIONS

STARSAT is a superb example of how two agencies may combine and leverage existing assets to accomplish a meaningful mission for minimal dollars. Additional funding to accomplish this program is expected to be ≈$2 million. This TM has summarized the joint NASA/Air Force laser space calibration experiments using the HI-CLASS on the advanced electro-optics system at the MSSS. The design and cost of the 25-cm-diameter microsatellite to include the GPS, laser beacon, power, and reflectance were addressed. The mission was found to be feasible both from a laser and microsatellite technical and cost standpoint. The mission shall enable experiments to provide accurate positions, rate, and signature measurements of the calibration spheres; demonstrate high-resolution tracking capability of small objects using the HI-CLASS AEOS; provide LEO data to allow the derivation of precision drag profiles; and support NASA/Air Force general requirements for laser space tracking technology demonstrations. Other benefits of the experiment data include calibrating radar and optical sites, completing satellite conjunction analyses, supporting orbital perturbation analyses, and comparing radar and optical signatures.

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A laser space calibration experiment is considered using the 12-J, 15-Hz high-performance CO_2 ladar surveillance sensor (HI-CLASS) system on the 3.67-m aperture advanced electro-optics system (AEOS). The objectives are to provide accurate range and signature measurements of orbiting calibration spheres, demonstrate high-resolution tracking capability of small objects, and precision drag determination for low-Earth orbit (LEO). Ancillary benefits include calibrating radar and optical sites, completing satellite conjunction analyses, supporting orbital perturbation analyses, and comparing radar and optical signatures. A global positioning system (GPS), laser beacon instrumented microsatellite about 25 cm in diameter will be deployed from a Space Shuttle Hitchhiker canister or other suitable launch means. Orbiting in LEO, the microsatellite will pass over AEOS on the average of two times per 24-hr period. An onboard orbit propagator will activate the GPS unit and a visible laser beacon at the appropriate times. The HI-CLASS AEOS will detect the microsatellite as it rises above the horizon, using Space Command-generated acquisition vectors. GPS data will be transmitted to the ground providing independent on-orbit, submeter accuracy location information for the microsatellite.

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